Simulant Materials of Lunar Dust
Requirements and Feasibility

Laurent Sibille

Lead Scientist for Space Resources Utilization

BAE Systems / NASA Marshall Space Flight Center

Ron Schlagheck

Element Manager for Space Resources Utilization

NASA Marshall Space Flight Center

Lunar Regolith Simulant Materials Workshop

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Marshall Space Flight Center - Huntsville, Alabama

Science Committee:

Paul Carpenter
MSFC/Bae Systems
James Carter
U. Texas - Dallas
David Carrier III
Lunar Geotechnical Institute

David McKay
JSC
Laurent Sibille
MSFC/Bae Systems
Lawrence Taylor
U. Tennessee- Knoxville

- Report on Lunar Simulant Materials: March 31, 2005 (interim); June 30, 2005 (Final)
  - lunar simulants needs, definition, production, cost & acquisition strategies
- Lunar Regolith Simulant Materials Requirements document
  - Will define specification standards for simulants and their production

"WE" WENT TO THE MOON

WHAT DID WE LEARN ?

We learned a lot from Lunar Samples

- >380 Kg (Apollo, Luna)

  … and the use of Simulants over the years

  - Apollo, Lunar Rover: over 34 types !
  - 1985 Minnesota Lunar Simulant 1 & 2 (Weiblen)
  - 1989 Workshop on Production and Uses of Lunar Simulants (McKay & Blacic)
  - 1991 Lunar Sourcebook (Heiken, Vaniman, et al.)
  - 1992 JSC-1 simulant (McKay, Carter, Boles et al.)
  - ~ 1993 FJS-1, Japanese Space Agency

Where are we now?

- MLS-1, JSC-1 are gone…
- Researchers make their own simulants or buy from small suppliers
- No materials made to simulate lunar dust

- In 2004
  - 17 projects funded by Exploration Systems Mission Directorate will study or develop technologies for lunar surface
  - Over 15 SBIR/STTR projects awarded that need lunar simulants
  - 1 SBIR (Phase I) to study production options of new lunar simulants

What lunar simulants do we need?

- Widely-accepted standard materials make it possible to compare technology performances
- The simulants developed must be relevant to the lunar exploration architecture
  - Planned Landing regions
  - Planned and funded Lunar activities
- The simulants must be prioritized
  - Spiral development of lunar simulants over the years?
    - 2005-2006 SMART-1
    - 2008 Lunar Reconnaissance Orbiter

And in what quantities?

2004-2005: Funded lunar activities

(NASA Exploration Systems Mission Directorate)

- In Situ Regolith Characterization: core drilling, geotechnical and mechanical properties, chemistry…
- Extraction of ice, hydrogen, volatiles, oxygen (polar and non-polar regions)
- Regolith handling: excavation, transport, berm building
- Dust mitigation

Workshop on Lunar Regolith Simulants
Approach

- Session 1 - **What simulant properties do we need to support the development of each lunar activity?**
- Session 2 - **What approach should be adopted to define a family of simulants? What combination of properties is needed for each simulant?**
- Session 3 - **How do you produce, characterize, validate and distribute these simulants?**

- Electronic Meeting System
  - ~ 60 Participants used networked workstations in parallel to provide knowledge and define requirements

Session 1 - Regolith properties to be simulated

- Use of a Knowledge matrix
  - Relates 'lunar activities' to 'regolith properties'
  - Assesses the importance of each regolith property
    - **HIGH (H)**: This property of lunar soil/regolith must be duplicated in a lunar simulant with high fidelity to assure a high degree of confidence in the technology developed using that simulant.
    - **MEDIUM (M)**: must be duplicated in a lunar simulant with medium fidelity
    - **LOW (L)**: does not need to be duplicated, but would be of added value.
    - **NOT REQUIRED (0)**: is not required in a lunar simulant for the development of the technology
    - **UNKNOWN**

Technology/Regolith Matrix

LUNAR ACTIVITY / REGOLITH PROPERTIES	1.0 Grain Properties	1.1 Grain Size	1.1 Grain Size	1.2 Grain Size Distribution	1.2 Grain Size Distribution	1.3 Grain Shape	1.3 Grain Shape	1.4 Grain Shape Distribution	1.4 Grain Shape Distribution	2.0 Electrostatic Charging Properties	2.0 Electrostatic Charging Properties	3.0 Magnetic Properties	3.0 Magnetic Properties	4.0 Geomechanical Properties	4.1 Mechanical	4.1.1 Fatigue	4.1.1 Fatigue	4.1.2 Strength	4.1.2.1 Tensile (1991)	4.1.2.1 Tensile	4.1.2.2 Compressive (1991)	4.1.2.2 Compressive	4.1.2.3 Shear (1991)	4.1.2.3 Shear	4.1.2.4 Grain Hardness (1991)	4.1.2.4 Grain Hardness	4.1.2.5 Coefficient of Friction (1991)	4.1.2.5 Coefficient of Friction	4.1.3 Flexural Strength - Bending Resistance (1991)	4.1.3 Flexural Strength - Bending Resistance	4.1.4 Fracture Properties (1991)	4.1.4 Fracture Properties	4.1.5 Impact Resistance (1991)	4.1.5 Impact Resistance	4.1.6 Rheology (Aggregate Flow Properties) (1991)	4.1.6 Rheology (Aggregate Flow Properties)	4.1.7 Angle of Repose (1991)	4.1.7 Angle of Repose	4.2 Physical	4.2.1 Thermal Properties	4.2.2 Bulk Density	4.2.3 Particle Density	4.2.4 Porosity	4.2.5 Surface Area	4.2.6 Permeability (Gas)	5.0 Agglutinate-Specific Properties	5.1 Friability	5.2 With Single-Domain Iron	6.0 Chemical Reactivity	6.1 From Surface Damage	6.2 As Volatile/Soluble Minerals	7.0 Chemical Properties	7.1 Bulk	7.2 Mineral	7.2.1 Mare	7.2.2 Highland	7.2.3 Polar	7.3 Glass	8.0 Modal Composition	8.1 Total	8.2 As a Function of Grain Size	9.0 Texture	10.0 Implanted Solar Particle-Specific (e.g., H, C, N)
1.0 Excavation		H	H	H	H	O	M	O	M	M	M	O	L			O	M		H	M	H	H	H	H	H	H	H	H	O	O	O	M	O	?	O	M	H	H		O	H	?	H	L	?		M	O		?			H?		H?	H?	H?	H		?	?	L?	?
2.0 Drilling			H		H		M		?		L		L				H			H		?		H		M		H		O		M		?		M		M		L	H	?	H	L	O		M	O		?	M?		L?		H	H	M?	L		?	L?	L?	M
3.0 Mobility Systems (Including EVA)		H	H	H	H	H	M	H	M	O	M	O	?			H	H		H	L	H	H	H	H	H	H	H	H	O	O	O	O	O	L	O	O	O	H		L	H	?	H	O	O		L	?		?	M?		L?		L?	L?	L	?		?	L?	L?	L
4.0 Regolith Transport		H	H	H	H	H	M	H	M	M	M	L	L			H	H		H	L	H	H	H	H	H	L	H	H	O	O	H	?	O	L	H	H	H	H		L	H	L	O	O	O		?	O		?	L?		L?		L?	L?	L	?		?	L?	L?	?
5.0 Physical Regolith Processing																																																															
5.1 Crushing			H		H		L		L		?		?				M			?		M		H		H		H		O		H		?		?		?		L	L	H	L	L	?		?	?		?	?		L?		L?	L?	M	M		?	M?	M?	M
5.2 Grinding			?		H		M		?		M		?				M			?		M		H		H		H		O		H		?		?		?		L	L	H	O	L	L?		?	?		?	?		L?		L?	L?	M	M		?	M?	M?	M
5.3 Sieving			H		H		M		M		H		?				M			?		L		?		L		H		O		L		?		H		?		O	L	H	O	O	?		?	?		?	?		L?		H?	H?	M?	?		?	?	M?	?
5.4 Beneficiation			H		H		M		M		?		M				L			?		M		M		L		H		O		M		?		M		?		M	L	?	O	O	?		?	H?		H?	M		L?		M	M?	M	?		?	H?	M?	?
6.0 Extraction Processes																																																															
6.1 Si and Metals Extraction (Including O2)		M	M	M	M	L	L	L	L	O	L	O	M			O	O		O	O	O	O	O	O	O	O	O	??	O	O	O	O	O	O	O	O	O	O		M	M	O	M	M	??		O	L		O	H		H										
6.2 Ice Extraction			M		M		??		L		L		H				O			O		O		O		O		??		O		O		O		??		O		M	M	M	M	M	L		O	O		O	L		H										
6.3 Volatile Extraction		L	H	L	M	L	L	L	L	O	L	O	M			L	O		L	O	L	O	L	O	L	O	L	O	L	O	L	O	L	O	L	O	L	O		M	M	M	M	M	??		O	O		O	H		M										
6.4 Beneficiation (Chemical)																																																															
6.4.1 Soil		H	H	H	H	H	H	H	L	L	L	L	L			O	O		O	??	O	H	O	O	O	??	O	??	O	O	O	O	O	O	O	L	O	O		??	M	M	??	??	M		O	??			H		H										
6.4.2 Rock		O	??	O	??	O	L	O	L	O	L	M	H			O	O		H	??	H	H	H	??	H	??	H	??	O	O	H	O	O	O	O	L	O	O		??	M	M	L	L	M		O	L			L		??										
7.0 Transformation Processes																																																															
7.1 Glass/Ceramic Formation		H	H	H	H	O	L	O	L	L	L	O	??			O	O		O	??	O	L	O	O	O	O	O	O	O	O	O	??	O	??	O	??	O	O		??	??	M	M	M	??		O	??		??	L		H										
7.2 Sintering, Concrete		H	H	O	H	O	H	O	??	M	??	O	M			O	O		O	??	O	??	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		??	M	M	H	H	??		O	O		M	??		H										
8.0 Radiation Shielding			H		H		L		L		L		H				H					??		O		O		O		O		M		M						L	H			H			M				L		H										
DELETED																																																															
10.0 Dust Effects & Mitigation																																																															
10.1 On Humans		H	H	H	H	H	H	H	H	H	M?	O	O			O	O		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O					M			O		H			H	H		H	H	H	H	H						
10.2 On Mechanical Systems		H	H	H	H	H	H	H	H	M	H	O	?			O				?	H	H	H	H	H	H	H	H	O	U	O	H	O	H	O	H	O	H		H	U	?	U	U	?		U	?		?	?		U		H	U	U	U		U	U	U	U
11.0 In-Situ Regolith Evaluation																																																															
11.1 Physical/Mechanical		H	H	H	H	H	M	H	M	O	H	O	H			H	M		H	L	H	M	H	H	H	H	H	H	H	H	H		H		H		H																						H					
11.2 Chemical			H		M		L		L		??		M				O			O		O		O		O		O		O		O		O		??		O		M	M	M	M	??	H		??	M		??	H		H					??		H	??	L	??

Session 2 - Simulant definition

- Concept of root & derivative simulants proposed and favored
- <u>Group 1 - Physical/Mechanical Processes</u>
  - **Resume production of JSC-1 Clone**
    - **address immediate needs (TRL 2-6), including geomechanical/geotechnical properties testing, and serve as a standard**
    - **Additives: chemical (ilmenite, anorthositic plagioclase), physical (larger particles >1mm)**
  - **Geologic sources for root & additive materials**
    - **High-Ti basalt (mare), Anorthosite (highlands)**
    - **Too little is known of lunar polar region geology**
    - **Exact geologic features of polar regolith may be secondary (polar environment is primary factor)**

Session 2 - Simulant definition

- <u>Group 2 - Physico-chemical Processes</u>
  - **JSC-1 adequate as base chemical composition**
    - **As a volcanic ash, it possesses some basic glass components**
  - **New root & additive materials**
    - **Basaltic tuff (glassy) at low end of Ti (Mare), Anorthosite (highlands)**
    - **Agglutinate material, iron phase, special glass content**
    - **Minerals as additives: Olivine, Ilmenite**
    - **Attention must be paid to minor and trace elements**

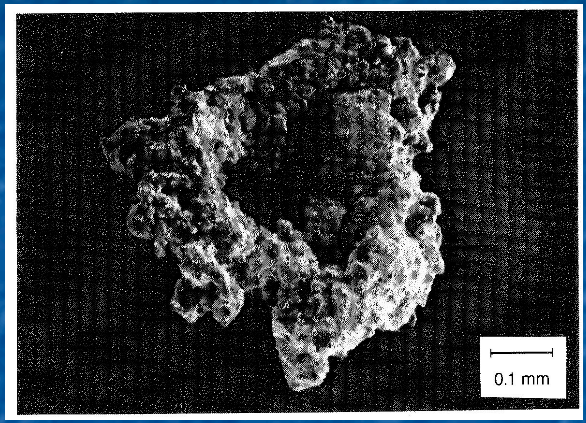
Session 2 - Simulant definition

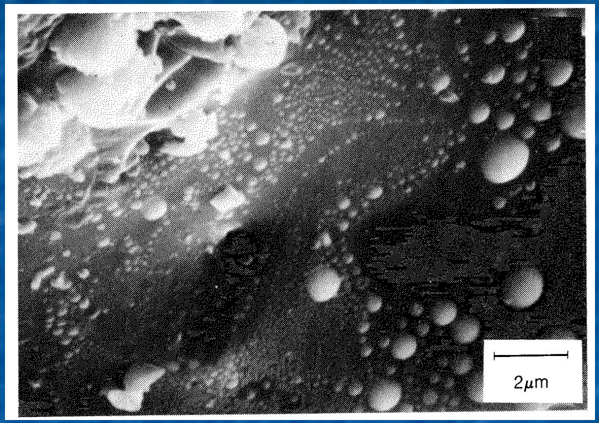
- Group 3 - Dust effects & mitigation
  - **For biological/medical applications, root simulants would have to be modified to increase fidelity to the actual lunar fines**
    - Close match to grain size distribution, agglutinates
    - < 20 microns particles are needed
    - Grain morphology & mineralogy
  - **New additive materials**
    - Use of pure mineral fines or others (SiO_2, C)
    - 'electronic simulants': modeling of dust behavior (electrostatic charging, irradiation effects, rheology)

Session 3 - Simulants production

- Needs for Lunar simulants estimated to be above 100t. Usage will be phased in time. Full estimates not complete yet
- Specific requirements defined for simulants characteristics and quality control
- Procurement options left open but NASA seen as ‘guarantor’ of quality and to perform curator functions
- Need for a database on simulants (part of quality control) and simulants usage & customers

Requirements on Lunar Dust Simulants for toxicity studies





(D. McKay et al., Ch.7, Lunar Sourcebook)

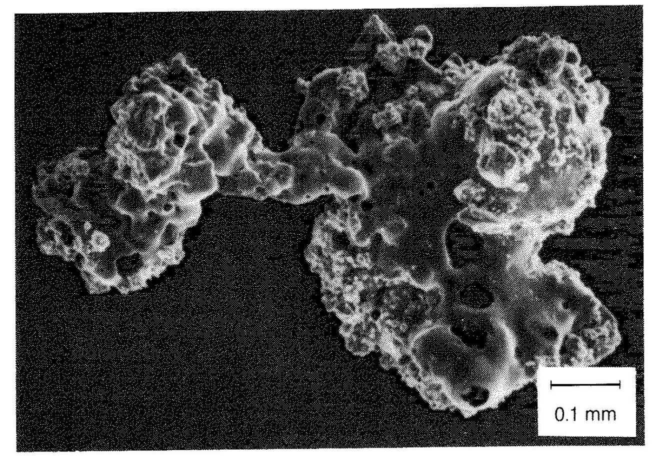
- Grain sizes (submicron to 20μm?)
  - Reduced gravity affects airborne particle streams/clusters
- Grain shapes
  - Elongation and aspect ratios, broken shapes, agglomerates
- Grain surfaces
  - Nano- and micro-roughness, porosity, electrocharging
  - Chemical reactivity (mineral phases, solar-wind elements (H^+, noble gases)
  - Amorphous & crystalline mix

Which dust properties are critical to understand lunar dust toxicity?

Adhesion
Sorption
Chemical Reactivity
Abrasion
Surface charge density
Interlocking shapes
Tensile strength (fracturing)
Solubility (mineral phases, amorphous phases)
Flocculation & Aggregation states (size distributions)
Thermal (heat absorption, transfer)
Optical (absorption, reflection, scattering)

Many properties dictated by size…

Lunar Environment Factors
10^{-12} Torr vacuum
Intense illumination (full spectrum)
Severe thermal gradients (+125C - ?)
Micrometeoritic bombardment
Oxygen free 'atmosphere

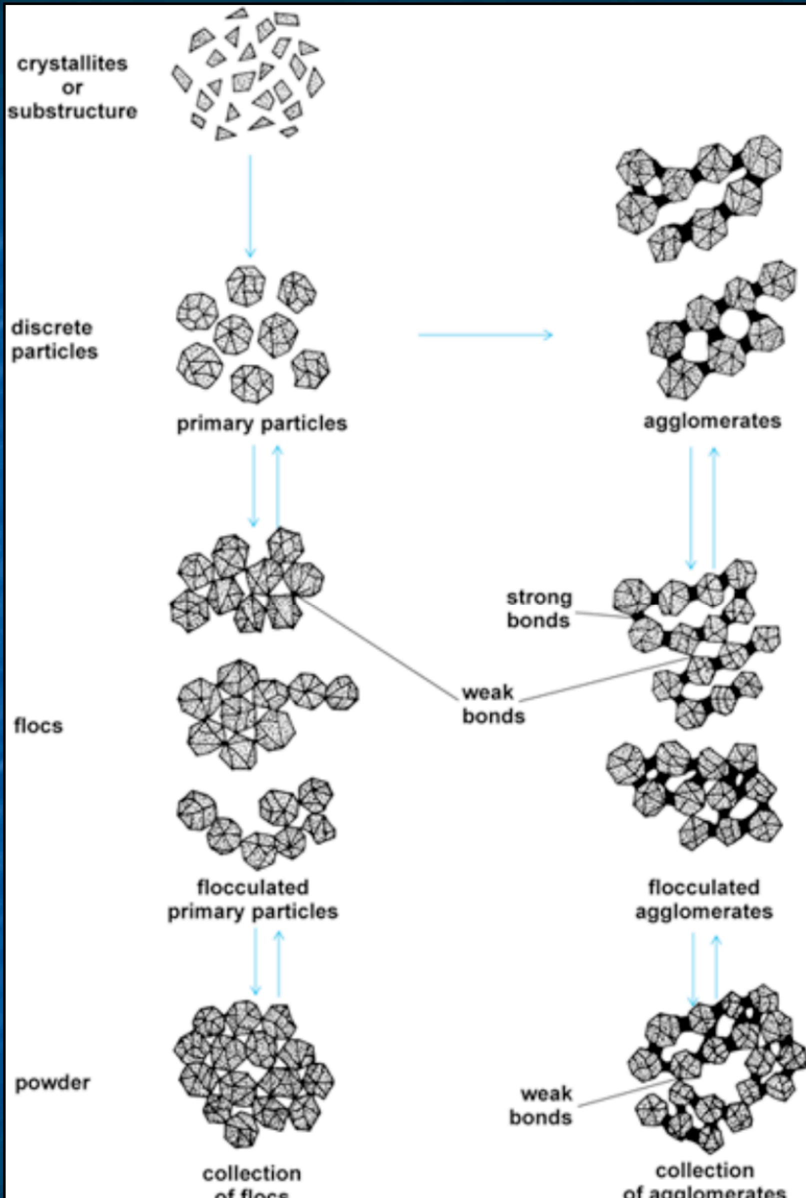


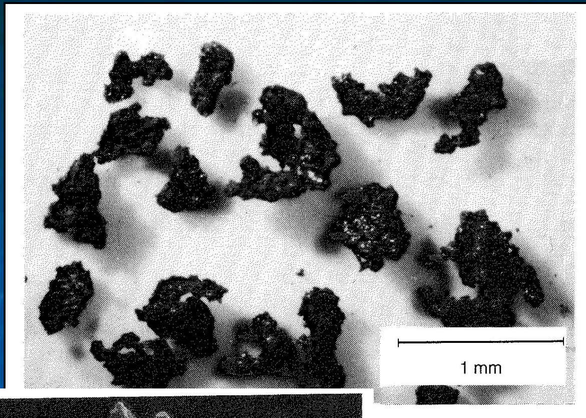
(D. McKay et al., Ch.7, Lunar Sourcebook)

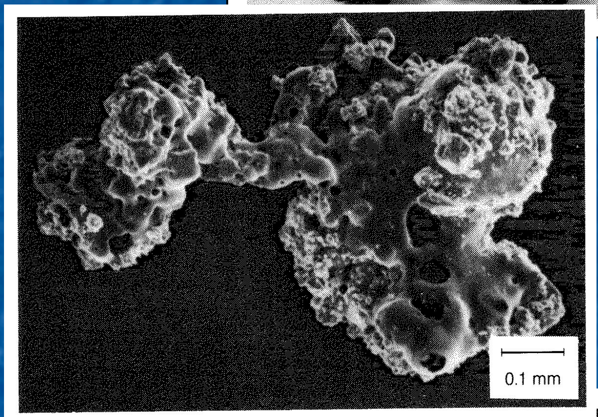
Human/Habitat Environment Factors
Atmosphere (O_2, pressure, H_2O, T°C)
Convective flows

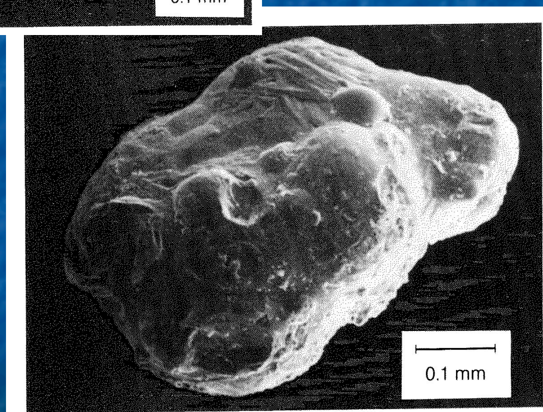
Feasibility issues
Dust simulants

- Feasibility will depend strongly on the cumulation of required properties
- Choice of starting materials (natural minerals or synthetic particles) dictates the ensuing processes
- Submicron fabrication available through many techniques
- Complex mineral chemistries at submicron levels likely to force the use of natural minerals









(D. McKay et al., Ch.7, Lunar Sourcebook)

Simulant particles
Production techniques

- Mechanical Dispersoids (wide size distribution)
  - Impact milling, comminution, disintegration
- Condensed Dispersoids (size uniformity, submicron control)
  - Vapor-phase condensation, crystallization, polymerization
  - Plasma synthesis, Sol-gel and colloidal processing (mixed oxide aerogels)
  - Ceramic whiskers, Nanophase iron synthesis

- As particle size decreases, shapes tend to become more spherical
- At small sizes (< 10μm), flocculation often results
  (Dynamic phenomenon)


2005…WE PREPARE TO GO BACK
NEW TECHNOLOGIES
NEW RESEARCH
NEW SIMULANTS

Workshop website:

- **http://est.msfc.nasa.gov/workshops/lrsm2005.html**

- We're looking for a few 'good' experts to complete the definition work of simulants…

  … contact Laurent Sibille or Ron Schlagheck

- Post-workshop activity (on-going):
  - Web-based data collection (open to experts who wish to contribute)